DOCUMENT RESUME

ED 477 693 SE 068 067

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TITLE	Design Principles of the ESCOT Math Environments.
INSTITUTION	Educational Testing Service, Princeton, NJ.
PUB DATE	2003-04-00
NOTE	19p.; Paper presented at the Annual Meeting of the American Educational Research Association (Chicago, IL, April 21-25, 2003).
PUB TYPE	Reports - Descriptive (141) -- Speeches/Meeting Papers (150)
EDRS PRICE	EDRS Price MF01/PC01 Plus Postage.
DESCRIPTORS	*Computer Software Development; *Computer Uses in Education; Educational Environment; Educational Principles; Educational Technology; Elementary Secondary Education; *Science Education; *Student Centered Curriculum

ABSTRACT

This paper describes the Educational Software Components of Tomorrow (ESCOT) project. The focus of the project was on principles that support problem-solving and learner-centered design issues, and the purpose was to garner lessons from a large educational software development project to share with the learning sciences and other interested communities who develop learner-centered software. The Identifying Design Principles in Educational Applets (IDEA) project, background of ESCOT, the Math Forum's Problems of the Week (PoWs), data mining for design principles, and design principles are presented. (KHR)

ETS Educational Testing Service

Distributed at AERA, April 2003

Design Principles of the ESCOT Math Environments

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Paper presented at the annual meeting of the American Educational Research Association (AERA)
April 21 to 25, 2003, Chicago, IL.

1 Introduction

The Internet is increasingly becoming a vehicle for various authors to publish educational software in the form of miniature applications (e.g., applets). The Educational Software Components of Tomorrow (ESCOT) project is an example of one such effort. After forging ahead with designing, publishing, and utilizing mathematics applets with many middle school students, we had a large database to draw upon for Identifying Design Principles in Educational Applets (IDEA). To begin the process of evaluating this existing library of educational software for mathematics, the authors of this paper focused on design principles that successfully support problem solving by drawing on such data as videos of students using the software and summaries of written student work. The focus of this project was not on user interface design specifically, but on principles that support problem-solving and learner-centered design issues. The purpose was to garner lessons from a large educational software development project to share with the learning sciences and other interested communities who develop learner-centered software.

Each piece of ESCOT software was accompanied by a context, a set of questions, and a Java-based applet (sometimes more than one applet) to help students answer the questions. They were posted to the public as part of the Math Forum's Problem of the Week (PoW) (http://mathforum.org/pow/) during 1999-2001, and called ESCOT PoWs (EPoWs).

Our approach to generating the design principles was to select a subset of the 42 EPoWs, for which data held the most promise for analysis (e.g., EPoWs that were revised from year 1 to year 2, a large number of student submissions). We then collected our expert opinions and built consensus ratings about each of the selected EPoWs. From that, we generated design principles, refined them, and categorized them. Each design principle has an associated intended effect for the user. We did empirical validation and further refinement of the design principles and of the intended effects by watching videos of students using the EPoWs. The resulting design principles fall into four categories (see Table 1).

Five of the authors were participants in ESCOT, each with different areas of expertise – middle school teacher, software developer, educational technologist, mathematics educator, and project evaluator. The remaining authors, not having been part of ESCOT, brought objective views about the software we set out to evaluate, and had complementary areas of expertise – teacher, mathematics educator, and technology designer.

The IDEA project's objectives were to identify principles that can guide the design of effective learning technologies through the analysis of applets created by the Educational Software Components of Tomorrow (ESCOT, NSF-funded) project, which is briefly described below. This work will contribute to the Center for Innovative Learning Technologies (CILT) Design Principle database [http://wise.berkeley.edu/design/] by adding design principles based on 25 concrete cases. We are hoping that with so many applets being analyzed against student data that a number of lessons can be learned about the design of powerful educational technologies. We intend to share our findings with the learning sciences community and other relevant communities. We regard these design principles and their validation as a starting point in a conversation. We hope that others will continue this conversation through the web site that houses the design principles as well as in other forums. Anyone interested in educational software design or the selection of educational software may find these design principles useful.

Table 1. Sample design principles, their categories, and intended effects.

Category	Sample Design Principle	Intended Effect
Motivation	Enable early reward for students (e.g. provide easy questions or activities they can do successfully)	get involved in the problem that leads toward producing a solution
Presentation	Make links between representations obvious and ungratuitous	less division of attention, understanding relationships
Support for problem-solving	History of actions	can lead to reflection, strategy tuning, and not wasteful duplication

2 The IDEA project: Connection to Theory

We began the IDEA project with the goal of extracting valid design principles from the ESCOT experiences. As researchers in instructional systems design have noted, what "valid" means may vary widely depending on what the principles are *for*—explanation and prediction or supports for the work of expert designers (Reigeluth, 1999). Should they be judged on their weaknesses (when they fail to work) or their strengths (when they are useful, regardless of whether they are comprehensive and "true") (Snelbecker, 1999). As George Fox once noted, "All models are wrong, but some are useful." Our goal in undertaking this project was to focus on the utility of these design principles while insisting on the highest degree of "truth" we could adduce—specifically, the principles had to be consistent with *all* the data we had at hand.

Simon (1969) defined design knowledge as a "science of the artificial" and highlighted that design science, in contrast to natural science, involves models that are relative not only to that which is designed (the artifact itself) but also, fundamentally, to the artifact's relationship to the setting and to external goals. It is in this spirit that we set out to learn what we could from the ESCOT experiences. In particular, we are highly aware that since we were doing an analysis of applets used in a very particular setting (the Problem of the Week context, in which the designers had little control over the context of use), we would only be able to make tentative models of how the applets influence problem solving.

While we only had one context in which to examine the interventions, we did have, in some cases, iterations on those interventions from Year 1 to Year 2 of the ESCOT project, and considerable access to the rationale for both the original versions of the EPoWs and successive iterations, in addition to the designers' own assessments of the success of their endeavors. Our goal, then, was to do a "post mortem"—to examine the principles that drove the design process and our post hoc interpretations of the outcomes, and to uncover the principles that we felt would be most useful.

Our goal was that the principles we uncovered would be ones with which we had some direct experience in the EPoW context, that either motivated the powerful successes or explained the clear failures, and that were consistent with the data at hand. In this sense, our work is like a design experiment (Brown, 1992; Collins, 1992), with one important exception: the extraction of design principles was done after the fact, and data was not collected during deployment for the explicit purpose of testing these design theories. We suspect that this sort of post-mortem analysis may be an important design-based research method that differs from the design experiment tradition. (Design-Based Research Collective, 2003; Hoadley, 2002)

We hope that these principles will be taken as objects for further discussion, examination, and eventually for adaptation in the design of other interventions, in the flexibly adaptive design sense (Schwartz, Lin, Brophy, & Bransford, 1999) with explicit acknowledgment that there is room for adaptation without "lethal mutation" (Brown, 1992), and with the knowledge that "your mileage may vary." In short, these principles are our best attempt to derive the most supported hypotheses from our data that deserve further examination by others in other settings.

Typically, design principles arise in one of two ways: either as a transcription of known techniques or strategies that have arisen through long experience (so-called "craft knowledge"), or through a combination of deduction from and extrapolation from known scientific theories of systems. Both rest on an empirical base, but in vastly different ways. For instance, an experience-based design principle in architecture may say that "thatched roofs made of wheat straw may be indefinitely and effectively maintained by removing damaged top layers and leaving the old base layers." (Hohle, 2003) This principle, based on the craft traditions of centuries (indeed, millennia) of roof thatchers in England, arose through experience with thatched roofs in the British climate. In contrast, a theory-driven architectural design principle might suggest that aluminum plumbing is preferable to iron or copper because it does not corrode as easily, based on (empirically-derived) theories of chemistry. However, both approaches have limitations. In the first case, the principle may have great weight of prior evidence, but if conditions change (as with the spread of wheat hybridized for food in Britain) the principle may fail (Hohle, 2003), and the lack of a mechanism or theory undergirding the principle may seriously hamper knowing when or why the principle will work. Similarly, theory-based design principles such as the aluminum-pipe principle may fail due to pragmatics in the situation that are not evident in the theory, such as the difficulty of joining aluminum piping systems to other metals without causing electrical currents which corrode both, or health concerns about aluminum in drinking water. This suggests that, ideally, principles should answer both to tradition and to theory, in addition to possibly being empirically tested in studies specifically designed to falsify them if they are untrue. We used a process that was both inductive (like craft knowledge) and deductive (like theory-generated knowledge) for selecting the most plausible design principles from the ESCOT experience. This process is described in detail below.

3 Background: ESCOT, the Math Forum, & PoWs

ESCOT was a very large, coordinated effort sponsored by the National Science Foundation. The project was led by SRI International in Menlo Park, CA, with key subcontractors at the Math Forum (now located at Drexel University); the University of Colorado, Boulder; the University of Massachusetts, Dartmouth; KCP Technologies, Inc (in Emeryville, CA); and the University of Missouri. All together, we had 7 major partners, and 34 organizations that contributed software, volunteers, and/or contractors. Key to the ESCOT network was a cadre of mathematics teachers who participated in design teams. A total of 19 teachers were involved, hailing from 11 different states.

The project title refers to "component software," and, indeed, much of our work revolved around a technical vision of modular, mix-and-match software tools (Roschelle et al., 1999). From these component tools, we developed a series of ESCOT Problems of the Week (EPoWs) in support of middle school mathematics. Over the course of two school years, integrated design teams, consisting of professional programmers, teachers, and educational technologists, produced 42of these EPoWs on a regular schedule. Each EPoW consisted of a motivating story, a set of driving questions, and an applet to help students solve the problem and answer the questions.

The Math Forum provided a context for exploring what would constitute a viable technical infrastructure for the development of interactive software to support student learning. In the Math Forum's well-established Problems of the Week (PoWs; http://mathforum.org/pow/), students read the problem, work on a solution either individually or with a peer or group, and write an explanation of how to obtain a solution. The students submit their solutions with explanations, receive feedback about their work, and are encouraged to submit a revised solution if there are areas that can be improved. The EPoWs were designed to follow this same arrangement.

The EPoWs were developed over two academic years. Student submissions were and continue to be part of the Math Forum archive (http://mathforum.org/escotpow/). Findings from Renninger et. al.'s (2001) study of student work with these problems suggests that students' competence and achievement account for differences in their problem solving. However, the computer-based learning environment appeared to override differences that would typically be found as a function of interest and self-efficacy with respect to students' abilities to connect to, generate strategies for, and be autonomous in problem solving. These differences may be due to the design of the EPoWs.

When the ESCOT project ended, it left a legacy of a large amount of data that could be mined. After the EPoWs were published on the Web, hundreds of student solutions were captured on the Math Forum web site; sessions of some students using the EPoWs were video taped; and design decisions made by the teams who created the EPoWs (see figure 1). These data informed the current effort of identifying design principles for educational software.

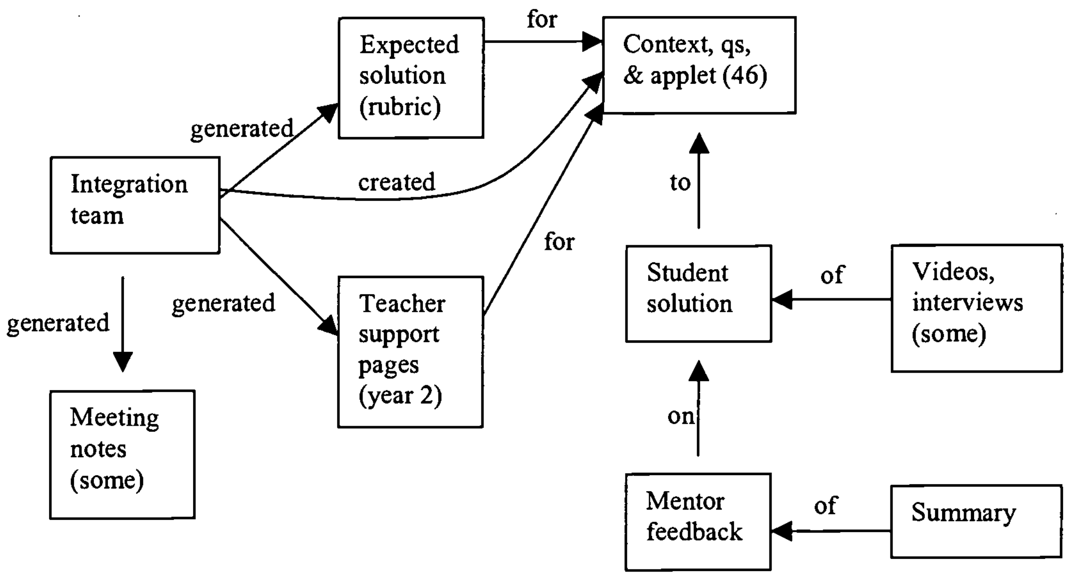


Figure 1. ESCOT Problem of the Week data

4 An Example EPoW: Fish Farm

During the second year of ESCOT (2000-2001), the Fish Farm EPoW (see Figure 2) was developed. It was purposely designed to give students access to different possible solution strategies and representations for making sense of the problem. This problem is open-ended in the sense that there are multiple strategies to use and three possible correct solutions. Although this problem can be solved using algebraic techniques, the intent of using the problem situation and tools in the java applet was to engage students in thinking about different strategies and solution paths, as well as part-part and part-whole reasoning and equivalent ratios. The bonus question was designed to induce a perturbation for students about the relationship between a part-part and a part-whole representation of a ratio. The students are asked to compare the part-part ratio of 1:2 to a pie graph showing a part-whole 1/3:2/3 representation. Many students intuitively think about a 1:2 ratio as representing a one-half situation and do not easily make the transition to a 1/3:2/3 representation.

The applet was created with a tank on its left side with 26 fish (13 males, 13 females) that the user could "drag and drop" into one of the three ponds to its right. As a fish is dropped into a pond, a numerical count and pie graph are updated to keep tally of the number of females and males and the percent of females and males in each pond. Once a fish is "dropped" into a pond, it will swim within the boundaries of the pond. The RUN button at the bottom of the screen is used to activate the applet so that the "updates" and "swimming" occur when a fish is dropped in a pond; however, a user can move the fish without hitting the RUN button. The STOP button deactivates the "updates" and "swimming" features. The RESET button will place all 26 fish back into the tank on the left, while the CLEAR button will erase all fish from the applet.

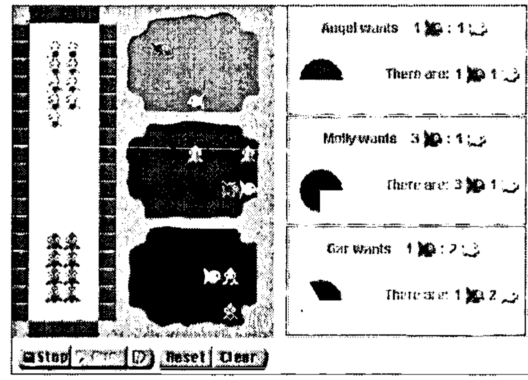
A Fishy Family: For their birthday, the Carp triplets received 26 tropical fish: 13 females and 13 males. They discussed ways to divide the fish among their three tiny backyard ponds.

Angel said, "I want the same number of male and female fish in my pond."

"Okay," said Molly. "I want three times as many males as females in my pond."

"Then I want twice as many females as males in my pond," Gar replied.

Is there a way to put all 26 fish into those three ponds, while giving each triplet what he or she wants? Use the applet to explore this question.



Interactive Java Applet

Questions:

1. How many male fish and female fish does each triplet get in his or her pond? Describe the work you did to find the solution. Sample questions you can answer: Into which pond did you put fish first? How many fish of each kind went into that pond? Why? What was your next step? How were you sure a pond had the correct ratio?
2. Given the 13 males and 13 females, what are ALL the possible numbers of male and female fish that would satisfy the ratio of 1 male to 2 female fish in Gar's pond? Explain why these different amounts are equivalent to the ratio 1:2.

Bonus: Explain why all possible answers in question 2 result in the same pie graph for Gar's pond.

Figure 2. Fish Farm EPoW.

The complete materials associated with this EPoW include (available online at http://mathforum.org/escotpow/solutions/solution.ehtml?puzzle=40): 1) the problem situation and questions, 2) an interactive applet, 3) a teacher support page with suggestions for pre and post activities, and 4) expected solutions. The solutions were prepared by the design team and used by mentors who provided feedback in response to a student's solution. After solutions were no longer accepted for an EPoW, it was archived along with comments from a lead mentor summarizing students' solution strategies, difficulties, and sample student responses.

Below is part of one 13-year-old's solution to the first question in the Fish Farm EPoW. Notice that the student described her strategy in terms of ratios, and used arguments about the properties of mathematical operations with ratios to justify her approach.

> *Angel had 8 male fish and 8 female fish in her pond. Molly had 3 male fish and 1 female fish in her pond. Gar had 2 male fish and 4 female fish in her pond. I first put one male and one female in Angel's pond, 3 male and 1 female in Molly's pond, and 2 males and 4 females in Gar's pond. I thought I could put the rest into Angel's pond,*

> *but I noticed that there was unequal amounts of males and females. So to make it equal, I put one more male fish and 2 more female fish in Gar's pond, that would still be the same as 1:2. That left me with the same amount of male fish and female fish, so they could all go into Angel's pond (that would still equal 1:1). Since I did everything slowly, I made sure that my amounts of fish were equal to the ratios. All I did was get the total amounts and then reduce them, and the reduced number should've equaled the ratio. I knew I got everything right when the bricks turned green.*

From this student's description, it appeared that several of the design elements in the applet provided tools for her to complete the task. Specifically, the displayed ratios allowed her to compare the pond's male-to-female ratio with the desired ratio so she could check if one ratio reduced to the other. It appeared that the bricks turning green also provided closure and confirmation that her solution was correct. This type of interaction and response was important for us to consider as we mined the EPoW data to identify design principles and intended effects of those principles.

5 Data Mining for Design Principles

5.1 Phase I: Expert Opinion

Design principles (DPs) were identified for the EPoWs using a six-step process. First, a subset of the EPoWs was selected for mining. Second, all the selected EPoWs were reviewed and a preliminary set of design principles was identified. Third, a popularity contest of the EPoWs was done to see how closely the experts agreed on their values. Fourth, design principles were generated by a consensus building approach. Fifth, the appearance of the preliminary set of design principles in each of the twenty-five EPoWs was noted. Sixth, the design principles were categorized into ease of applet use, motivation, presentation, and support for problem solving.

1. **EPoW selection**. Of the 42 EPoWs that were developed for the ESCOT project, we narrowed the bank to draw on for the purpose of mining design principles. Two key points were considered: 1) there were at least 20 submitted student solutions, or 2) the EPOWwas part of a 1st-2nd year generation pair. The 25 EPoWs that were mined can be found in Appendix A.

2. **EPoW review**. We followed a top-down approach to identifying the design principles. We, as "experts" from a variety of disciplines and perspectives, reviewed each selected EPoW, noted what characteristics we valued with respect to its mathematical purpose. We also reviewed the design rationales from the design teams and mentor summaries of students' typical solutions and strategies for each EPoW. These were the building blocks from which the design principles were generated.

3. **Overall Quality Ranking**. As a starting point for our discussion of principles for the design of high quality applets, we individually ranked the overall quality of the selected EPoWs. We each brought different expertise to the table, which informed our perceptions of the EPoWs. The ranking exercise helped bring these differences of opinion to the fore. The activity also initiated a valuable discussion on how individual

applet features combined to give an overall impression. We then took the individual rankings and, after some discussion, aggregated them into a single list of rankings. The EPoWs and their quality rankings are listed in Appendix A. The highest ranked EPoWs were Galactic Exchange, Search and Rescue (year 1), and Fish 2. The lowest ranked EPoWs were Scale and Bowl, Rock Paper Scissors 1, Fractris, and Marabyn.

4. **Design Principle generation and consensus building**. At this point, we combined the lists of design principles that we had generated in the small groups. We then reviewed this larger list, combined and came to consensus on definitions, and reduced the list of design principles to ones that were evident in several EPoWs.

5. **DP appearance in the EPoWs**. We took the list of principles that were found in a subset of high and low ranking EPoWs and noted which EPoWs followed and violated each. Small groups consisting of 2-3 researchers took each of the design principles and noted where they appeared and did not appear in each of the EPoWs. Each of the small groups did this for a common set of EPoWs, coming to consensus on the definitions of the DPs. Once we reached consensus, we did the mapping onto the additional EPoWs.

6. **DP categorization**. The design principles were categorized into ease of applet use, motivation, presentation, and support for problem solving. We decided that the ease of use DPs encompassed principles of user interface; thus we subsequently focused our efforts on the later three categories. These are described in more detail in the Design Principles section.

5.2 Phase II: Empirical validation

Once design principles and intended effects were hypothesized, videos of students interacting with some of the EPoWs were examined. The videos were sampled to include the following:

1. Two high ability 8th grade boys using Fish Farm 1
2. Two lower ability 8th grade girls using Fish Farm 1
3. Two low ability 8th grade students (one boy and one girl) using Fish Farm 1 while working with a pre-service mathematics teacher
4. Two lower ability 8th grade girls using Scale n Pop

These videos were original data sources collected from several research projects conducted by various members of the ESCOT team, including the Renninger et. al. (2001) study of student work with the EPoWs and the Stohl research program (Stohl, 2003; Stohl, under review). In each video, students were encouraged to think aloud while working in pairs at a computer with access to paper and pencil. The video images were captured in such a way to observe both verbal and non-verbal information about how the students interacted with the EPoW. The ability to observe students directly interacting with the applets was useful for coding.

Our intention for examining the videos was to locate evidence to support whether or not a design principle (DP) was followed, and whether or not an intended effect (IE) occurred. Thinking about these options as a 2x2 matrix allows us to see four possible outcomes (see Figure 2).

Table 2. Coding for student videotape data.

	Design Principle Followed	**Design Principle Violated**
Evidence of Intended Effect Displayed	*FE (followed, with effect)*	*VE (violated, with effect)*
No Evidence of Intended Effect Displayed	*FNE (followed, no effect)*	*VNE (violated, no effect)*

These four outcomes (FE, FNE, VE, and VNE) were used as we coded video segments. Each researcher had a chart that listed each DP, IE, and space for recording descriptions of segments from the video (including timestamps) that provided evidence supporting (FE and VNE) and evidence against (FNE) a design principle (see Table 3 for examples). For the fourth case, when a DP was violated but there was evidence that an IE was achieved (VE), no conclusion could be made about whether the evidence supported or refuted a design principle. Thus, a segment coded as VE was inconclusive and not used to support to refute a DP and IE.

Table 3. Examples of evidence of design principles in several video sessions.

Category	Design Principle	Intended Effect	Evidence	Video Session
Motivation	Enable early reward for students (e.g. provide easy questions or activities they can do successfully)	get involved in the problem that leads toward producing a solution	FE (min 5) They were happy when the balloon released. FE (min 17-18) They were happy when the balloon enlarged for the improper fraction booth.	Scale n pop, two girls
Presentation	Links between representations should be obvious and ungratuitous	less division of attention, understanding relationships	FE (min 11-13) One girl knew to use the sums instead of counting the fish. FNE (min 11-13) The other girl didn't know to use the sums. VNE (min 3-6) The girls expected the other representations to be updated when they did something.	Fish 1, two girls
Support for problem-solving	Everything in there (questions, interface elements, activities) should have a sound pedagogical reason	more coherent, less accidental, better learning environment	VE (whole) The equation didn't seem necessary. FE (min 5-6, 17-18, 20-22) The series of buttons allowed them to make judgments and adjustments before releasing. FE (whole) Because the last question was about numerator and denominator, forcing them to type in only standard fractions was okay. VNE (whole) The decimal new diameter had no good purpose and wasn't used.	Fish 1, two boys

The videotape data were first reviewed by five of the researchers in one group, in successive 3-minute segments in order to provide evidence for the design principle being effective. During this time, we paused to write down everything we thought relevant after each segment and to discuss our observations. Second, detailed notes of students' work with the EPoW were compiled in order to evaluate the correspondence between assessed IEs and evidence of these effects based on student activity (see examples in Table 3.) After we watched a student work session, we compared the codes and evidence generated independently by five members of the research team. For each DP, the codes were shared, compared, and discussed until consensus was reached. Within each video analyzed, evidence was provided for almost all DPs. In addition, all four codes (FE, FNE, VE, VNE) were evident in the analysis of the video segments.

We had conversations about the role of student data in our design principle work. Since the data was not obtained from studies that were designed to validate the design principles, the contribution of the data is to give examples, both pro and con, for specific principles. From these, hypotheses can be generated from which future studies can be designed.

6 The Design Principles

After we generated, refined, and organized the design principles, we came up with a list of 23 principles, organized into three categories. Each design principle is listed with intended effects, as described in the student data section above. The resulting categorized list is located in Appendix B.

6.1 Three Categories

During our last session working with the design principles (DPs), we identified three categories that the design principles fall under: *Motivation, Presentation,* and *Support for Problem-Solving*, each of which is described below. During the categorization process, we collapsed some of the DPs into others, resulting in a new total of 23 principles. The categorized list, along with intended effects, is located in Appendix B. As mentioned previously, there were a number of principles that fell under the realm of User Interface design, and we did not address those in our list since they are covered extensively in the literature.

Motivation: These design principles promote motivation, including staying on task, showing excitement about the process, etc. They include such principles as familiar problem context and enabling early reward for students. This category has four design principles.

Presentation: The simplest way to think about these design principles is in terms of proofreading for the intended audience. In a sense, this is the counterpart to the "Ease of Applet Use" category for everything other than the applet. Some principles that are addressed are clarity of the context and the questions and the use of professional conventions. Some principles get at applet implementation issues when they're not about the *use* of the applet, but about the *meaning* of the things in it. For example, the linked representations need to be obvious, or draw attention only to things that support the problem solving. The effect we expected was that the understanding of the problem and all its facets not be impaired. This category has seven design principles.

Support for Problem-Solving: A plurality of the principles falls into this category with its 12 design principles. All these design principles are intended to facilitate problem solving, including things like allowing multiple solution paths, multiple entry points, appropriate feedback, and rewarding strategic thought.

6.2 Interactions between Principles

These design principles do not stand alone, as each EPoW uses a number of design principles. Interactions between the design principles must be considered in the design or in the selection of educational software.

Toward this end, one of our goals is to have a ranking of important design principles. While evaluating the design principles that capture the EPoWs, these interactions were noted. These are some examples of how some design principles are more important than others, though the ordering may not be clear all the time:

1. *User expectations of artifact and interface design are met* vs. *Attention is drawn to the important information*. Fish2 was designed so that as each fish is scooped out of a pond, a running total is incremented, and a pie chart updated to reflect the ratio of males to females that have been selected. As was documented with students using Fish1, students expect the updating to occur. However, the fish are constantly moving around the pond using animation, and this distracts students from seeing the two representations that show the mathematics of what is occurring, which can subsequently affect their problem solving ability.

2. *Graphics are great* vs. *Attention is drawn to the important information*. In Hispaniola a graphic artist developed pictures and animation that help the student fill cups with water, according to the constraints described in the problem. However, students have to pay a lot of attention to the moving around of cups to the spigot and funnel, and therefore cannot pay a lot of attention to the history list that shows them what they have achieved and what they still have to achieve.

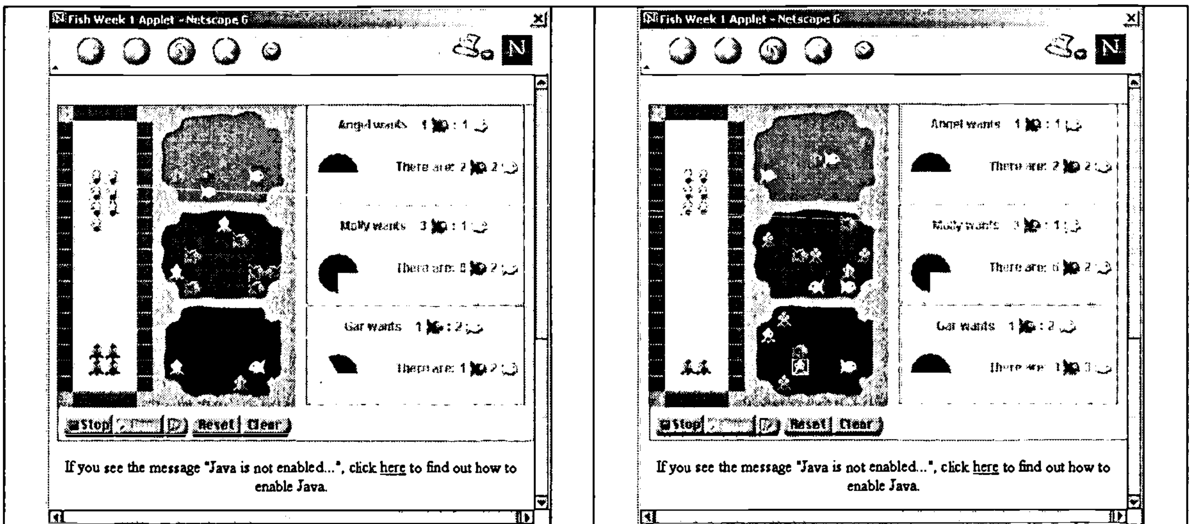
3. *History of actions* vs. *Follow conventions*. In Fish2 a history of actions is recorded, which helps students see trends in their selections. However, you must remember to *save* in order to obtain a history. The latter goes against what one would expect in the interface, given that the history is very helpful in solving the problem.

6.3 Illustrations

In addition to the previous videos used for empirical validation, four video tapes of eighth grade students working in pairs with a pre-service teacher on the Fish Farm problem (Stohl, under review) were analyzed from the perspective of students' problem solving (Stohl & Hollebrands, in progress). The hypothesized design principles (DP) that support problem solving and their intended effects (IEs) were used to gauge whether observed actions and effects aligned with or contradicted the hypothesized IEs. The designers of the Fish Farm EPoW followed many of the DPs related to problem solving (e.g., allowing multiple entry points, supports multiple approaches and solution strategies, uses dynamic multiple representations); however, several DPs were not followed (e.g., history of actions, programming of applet supports level of accuracy necessary). To illustrate the four coding categories (FE, FNE, VE, VNE), consider the followed DP of "uses dynamic multiple representations" and the violated DP "history of actions."

Multiple Representations. Fish Farm uses multiple representations to provide a visual display of male and female fish. As the iconic fish are dragged and dropped in the ponds, the ratio count and pie graph displays are dynamically updated. The general IE for this DP is to help students: 1) develop representational fluency, 2) facilitate better understanding of the problem, and 3) be engaged in mathematical thinking. The ratio count and pie graph are intended to display the current status of the part-part and part-whole relationship between males and females in the pond that can facilitate a better understanding of the problem and engage students in thinking about how to adjust their strategy for distributing fish. In addition, it is intended that the ratio counts can alleviate having students count fish in the ponds and to promote a transition between reasoning part-part and part-whole about the ratios.

Across these four videos, there were examples where students' observed actions and effects of these actions were aligned (FE) and not aligned (FNE) with the IE for multiple representations. One pair of students established the link between the representations and the number of fish in a pond early on and subsequently did not have to count the number of fish in the pond (FE). With prompting from the pre-service teacher, these same students also made connections between the ratio and the pie graph and were able to connect the part-part ratio to the idea of a fraction in the pie graph (FE). Another pair of students mistakenly reversed the ratio of 1 male to 2 female for Gar's pond and added 2 males and 1 female to Gar's pond (see Figure 3) without apparently using the ratio count and/or pie graph to notice that the 3:3 was incorrect (FNE). However, because many students initially anticipate a ratio of 1:2 to result in a pie graph that shows ½ red and ½ yellow, it is possible they used the pie graph accordingly with that expectation and did not make the connection between the 3:3 ratio count, the pie graph, and the 1:2 expected ratio displayed for Gar's pond. It is also appears that they did not notice the difference in the pie graphs for Gar's pond from the before state (figure 3A) and the after state (figure 3B). Later in the session, these same students reset the applet to try to find a second solution. However, they forget to press the "Run" button and when they placed one male and one female fish in Angel's pond, the representations did not display. The students pointed to the pie graph and the ratio count and asked why the displays were not there. This provides evidence that the students expected the representations to be displayed and were in the habit of attending to these displays (FE). Yet another group seemed not to use the representations in their problem solving (FNE). They seemed to focus on the static fish in the tank and often counted the swimming fish in the ponds and occasionally referred to the updating ratio counts (FE). These students made no reference to the pie graph or connections between the fish, ratio and pie graph (FNE). However, these students successfully solved the problem and their non-use of the multiple representations did not seem to hinder their problem solving (FE).



A: All ponds have correct ratio. Gar's pond currently has 1:2	B: After placing the reversed ratio of 2:1 in Gar's pond, ratio count now 3:3

Figure 3: Consecutive states of the Fish Farm EPoW.

History of Actions. Fish Farm did not include a History of Actions feature to keep track of students' correct or incorrect solutions and actions. It was hypothesized that a History of Actions would encourage student reflection, strategy tuning, and reduce duplication of incorrect solution strategies. For three of the student pairs, the absence of a History of Actions seemed to hinder their problem solving (VNE). All three pairs were able to find one solution to the problem, but when they were asked to find a different second solution they had difficulty remembering their first solution. Recalling the first solution was necessary for students to determine if their second solution was different. For example, one pair of students quickly found their first solution to the problem by placing 3 male and 3 female fish in Angel's pond, 6 male and 2 female fish in Molly's pond, and 4 male and 8 female fish in Gar's pond. When challenged to generate a second solution, these students made progress but repeated what they had done the first time. It was the pre-service teacher, rather than the students, who recalled that their current strategy would result in the same solution. However, for another pair of students the absence of a History of Actions did not seem to impede their work at all (VE). However, this pair used paper to record their first solution and they were able to find a second solution without relying on the pre-service teacher to recall what they did the first time. These examples could provide evidence to support the argument that memory aids (pre-service teacher, paper and pencil, History of Actions) can assist students in solving problems.

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Appendix A: Highest and Lowest Ranked EPoWs

	Number of Rankings as	
Name (Chronological order)	Highest	Lowest
Pirates & Diamonds		111
Scale n Bowl		11111
Llamas		11
Llamas 2		
Rock, Paper, Scissors		11111
Rock, Paper, Scissors 2		
Earthquake		1
Earthquake 2		
Earthquake 3	111	
Earthquake 4	111	1
Shoelaces		11
Shoelaces 3	1	1
Search and Rescue (year 1)	11111	
Elephant	111	
Hispaniola	11	
Galactic Exchange	1111111	
Marathon Graphing		111
Scale n Pop	1	1
Search and Rescue	111	1
Graph Zooming		
Fish	11	
Fish 2	11111	
Fractris	1111	
Marabyn		11111
Pythagoras' Mystery Tablet	1	111

Appendix B: The Categorized Design Principles

Category	Design Principle	Intended Effect
Motivation	1. Familiar problem context	motivation
	2. Use second person voice	immersive, motivating, creates ownership for student
	3. Enable early reward for students (e.g. provide easy questions or activities they can do successfully)	get involved in the problem that leads toward producing a solution
	4. For videogame-like activities, interactivity, high-quality graphics, etc. should match user expectations for playability	get game players to take seriously and students continue with the problem
Presentation	1. Question, cover story and/or introduction should be clear, unwordy, unsuperfluous	students get started quickly because they know what to do
	2. Proofread text, labels, etc, with target users and age range in mind	reduce distractions or snag, increased focus on learning issues
	3. All other things being equal, use professional conventions for content domain	familiarity, enculturation
	4. Make links between representations obvious and ungratuitous	less division of attention, understanding relationships
	5. Use high-quality graphics and other media (e.g., still graphics, audio, animation)	better understanding of the problem.
	6. Draw attention only to things that support the problem solving	more on task, more focus on important issues that will help the student to solve the problem
	7. Make everything described in the question obvious in the applet; align interactive and noninteractive parts	students oriented more quickly. The applet supports student solutions to the questions.
Support for problem-solving	1. History of actions	can lead to reflection, strategy tuning, and not wasteful duplication
	2. Everything in there (questions, interface elements, activities) should have a sound pedagogical reason	more coherent, less accidental, better learning environment
	3. Allow multiple entry points (e.g., ability, experiences, preferences, styles...)	more students might have many ways to get started, get involved
	4. The E-POW supports multiple approaches and multiple solution strategies (e.g., questions and/or applet)	students can use different strategies to solve the problem - more students should be able engage in mathematical thinking
	5. Use dynamic multiple representations appropriately (linked/notlinked, multiple or single sources of control)	develop representational fluency. Facilitate movement toward better understanding of the problem. More students should be able to engage in mathematical thinking.
	6. Give students opportunities to make predictions, commit to them, and examine outcomes	students may revise their solution strategies. Way to make learnable moment

	7. Thoughtful strategic use of the tool should be rewarded more than random use	less try-and-trash, more thinking
	8. Make a pedagogical decision about whether closure is needed.	sense of accomplishment
	9. Applet should give appropriate status feedback (say the right thing at the right time in the right way)	appropriate challenge but doesn't get too far off track.
	10. Programming of the applet supports the level of accuracy necessary for problem solving	less wasteful hairsplitting
	11. Make effort involved in an activity proportional to the importance of what is needed to solve a problem (aside from programming for accuracy)	more likely to stick with the problem. Students attend primarily on relevant factors. Less busywork in the student's mind.
	12. Technology should add value	technology is an integral and essential element in the problem solving process. Students use the technology as an essential part of their problem solving.

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